Laser Instrumentation, Technology & Calibration

The Laboratory for Terrestrial Physics includes the Laser Remote Sensing Branch which is a unique instrumentation development and calibration branch.

The Laser Remote Sensing Branch's mission is to develop laser remote sensing techniques and instruments for scientific measurements of the Earth and planets. Activities include developing and demonstrating new measurement techniques, conducting experiments, and developing ground-based, airborne, and spaceborne laser sensors (lidars). The Branch's work is usually multidisciplinary, and involves theoretical and experimental activities in applied physics, technology development and instrument engineering. Some activities include planning and participating in scientific field campaigns, analyzing the laser measurement and laser sensor performance, acquiring and interpreting lidar data, and developing lasers, optics, and detector components. The Branch's work often involves collaborations with application scientists within Goddard, at universities or other government laboratories, and with researchers and engineers who specialize in lasers and electro-optics.

The organization manages and operates the NASA Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) Networks in support of global space geodesy and Solid Earth geodynamics. The branch also provides the Earth science research community with a broad range of expertise in calibration and characterization of optical remote sensing instrumentation from the ultraviolet to the near infrared and through all phases of spaceflight.

The accomplishments of the branch have been broken down by topic: Spaceborne, Airborne, and Ground-based lidars, Laser Technology R&D, Satellite Laser Ranging, and Calibration.

Initial Measurements of Geoscience Laser Altimeter System (GLAS) on the ICESat Mission

The Geoscience Laser Altimeter System is a next generation space lidar developed for precise measurements in Earth orbit from the Ice Cloud and Land Elevation Satellite, ICESat. GLAS was developed by a Goddard instrument team lead by the Laser Remote Sensing Branch. The ICESat mission was launched from Vandenberg, CA in January 2003.

GLAS was activated in February 2003, using the first of its 3 lasers. The initial measurement campaign was interrupted in mid-March by an anomaly with Laser1. An investigation team was formed and reported in August a problem found with a pump diode part in all lasers. The science measurement campaigns were replanned, and resumed in the Fall using Laser 2 and included activation of the receiver's 532nm photon-counting detectors. The GLAS measurements from these first two observational campaigns were summarized in more than 30 papers at the Fall AGU meeting in December 2003. A few highlights of its initial measurements are shown below.

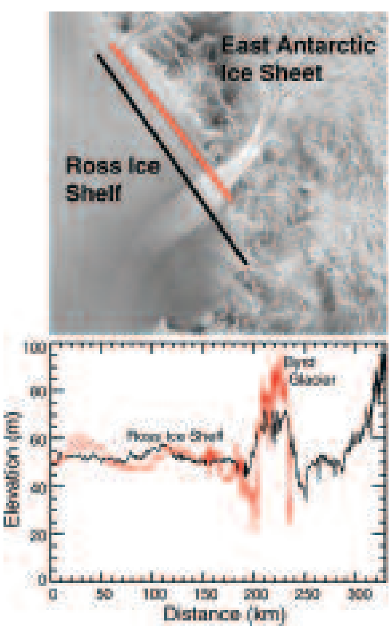

Figure 1. Portions of two sample GLAS elevation profiles above show changes to the Byrd Glacier as it flows from East Antarctica, crosses through the TransAntarctic Mountains, and then discharges into the Ross Ice Shelf. The red-line, more upstream, shows a thicker, narrower glacier. The black line (further into the ice shelf) shows that ice flow has caused the Byrd to become wider and thinner. Rough surfaces, such as crevasses, are also evident, which have never before been observed from space with this vertical resolution.

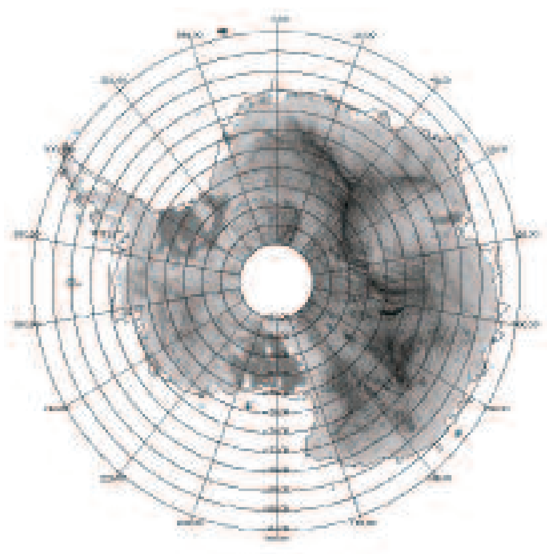

Figure 2. An initial shaded relief map of the vertical structure of Antarctica from GLAS and ICESat's altimetry profiles. Features like ice shelves, divides, and the flat ice over Lake Vostok (~105° E). The GLAS measurements over Lake Vostok show standard deviations of < 2.5 cm, which is 10 times more precise than any other space lidar.

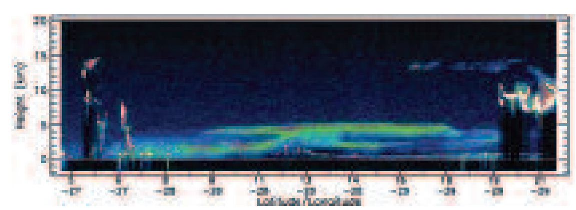

Figure 3. An example of a high-resolution atmospheric backscatter profile, measured by GLAS at 532 nm, over the Atlantic Ocean west of Africa. It shows clouds and a multi-layer aerosol dust layer from the Sahara desert. The GLAS 532 nm receiver has sufficient sensitivity to profile the height and structure of the atmospheric boundary layer, and with averaging, to measure the profile of Rayleigh backscatter from the atmosphere at night.

Contact: James Abshire, James.B.Abshire@nasa.gov

On-Orbit Laser Pointing Determination for the ICESat Mission

Background. The Geoscience Laser Altimeter System (GLAS) incorporates a Stellar Reference System (SRS) for directly measuring the pointing angle of the outgoing laser beam for each shot fired at 40 Hz to an accuracy of less than 1.5 arcsec (1-sigma). The SRS is comprised of two star trackers, one having a narrow field of view for increased accuracy, a hemispherical resonant gyro (HRG) and angle preserving beam steering optics. Absolute laser pointing determination is achieved by simultaneous laser far field imaging and attitude determination in the system. This is the first time that a spaceborne laser altimeter system directly measures the pointing uncertainty of the laser beam resulting in a highly accurate altimetry measurement.

Laser Position Monitoring. The narrow field of view star tracker is comprised of two CCD arrays operating at 10 Hz (Laser Reference Sensor, LRS) and 40 Hz (Laser Profiling Array, LPA) with the same plate scale. The LPA has 80 x 80 pixel array and detects the laser image only while the LRS has a 512 x 512 pixel array and detects the laser image along with a star and an optical fiducial at 10 Hz. Shot-to-shot centroid motion, as well as orbital variations for the laser position in the LPA and LRS are shown in Figure 1.

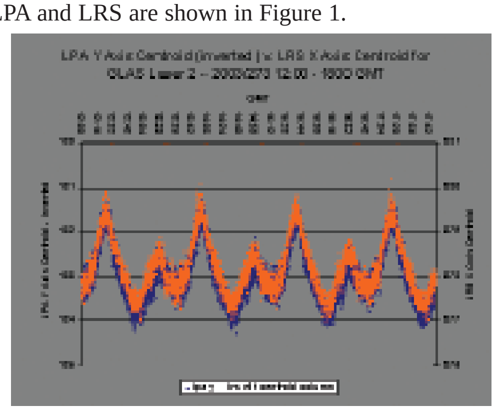

Figure 1. Laser spot centroid motion for three orbits, as seen in the 10 Hz lRS and 40 Hz LPA. The orbital period corresponds to large peaks. The vertical axes are in arcseconds.

The high resolution of the camera system for laser centroids can be seen from the small spread of the trace from shot to shot jitter. A regular orbital pattern can be observed. The smaller secondary peaks are coincident with terminator and are therefore due to thermal movements of the instrument.

LRS Star Tracking. The LRS provides star images as shown in Figure 2. The star image shows the smear along the flight direction of about two pixels. Star centroids for typical star observations is presented in Figure 3.

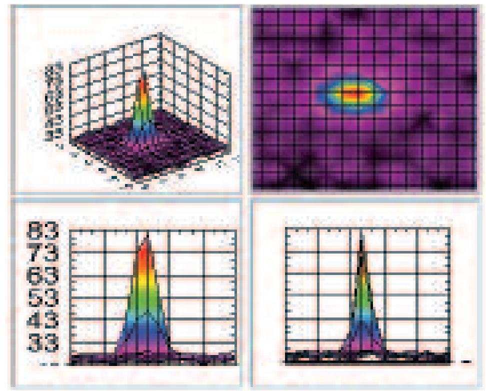

Figure 2. Star image recorded by LRS (star magnitude 5.6). The smear is due to movement during image capture due to spacecraft motion

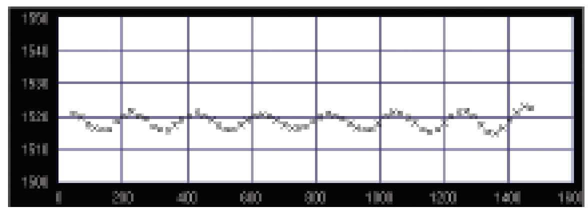

Figure 3. Example of centroid trajectories across the FOV for star observations. The interval between points is 100 msec.

Clear oscillation pattern for the spacecraft in roll can be seen. This oscillation, which varies from 10 to 50 arcsec in amplitude, has about a 1 Hz period and has been associated with the incremental motion of the solar panels at the same frequency. Oscillations in spacecraft pitch or roll as small as 0.5 arcsec have been observed. The high spatial resolution of the LRS permits observation of these very small angular motions.

On-Orbit Characterization. The relative motion between the narrow FOV star tracker (LRS & LPA) just described, and the wide FOV instrument star tracker (IST) is measured using a collimated reference source (CRS) firmly attached to the IST. The comparison on boresight displacement as registered from star observations can be carried out just from common star observations in the two cameras. Other means for checking the laser pointing accuracy include ocean calibration sweeps and uplooking ground photography of the laser beam. A detailed description of the SRS hardware along with the other calibration techniques can be found in (AAS 04-077 2004).

J.M. Sirota, P. Millar, C.T. Field, D. Mostofi, E. Ketchum, C. Carabajal and S. Luthcke, "Laser Pointing Determination System for the Geoscience Laser Altimeter on ICESat. Initial In-flight Performance Assessment," AAS (04-077) 2004.

Contact: Pam Millar, Pamela.S.Millar@nasa.gov

Mercury Laser Altimeter (MLA) on the MESSENGER Mission

MLA is one of the primary instruments on NASA's MESSENGER (Mercury Surface, Space Environment, Geochemistry and Ranging) Project, under NASA's Discovery Program. MESSENGER, the first spacecraft ever to orbit the planet Mercury, will be launched in July 2004 and will enter Mercury orbit in April 2009, after two flybys of Venus and two of Mercury along the way. Because of the limited fuel capacity, MESSENGER will stay in a highly elliptical orbit around Mercury. MLA and other instruments will perform measurements only during part of the orbits about the periapsis. The MLA measurement will provide mapping and detailed characterization of the planet's surface and the shape of the northern hemisphere.

Because of the relatively close distance to the sun, MESSENGER and the payload will have to operate under severe thermal environment with large temperature variation and fast transient. During part of the year the spacecraft is constrained to pointing the instrument deck to the ecliptic south and MLA has to perform its measurement at a large off-nadir pointing angle. These operating conditions and spacecraft mass and power constraints pose several major technical challenges to the MLA design, fabrication, and testing.

The MLA Instrument design is inherited from MOLA and GLAS. It is designed and built by a GSFC instrument team led by the Laboratory for Terrestrial Phyics. The laser was designed and built by the Laser Remote Sensing Branch's Space Lidar Technology Center (SLTC). The total weight of the instrument is 7.3kg. The peak electrical power consumption is 23W. The data rate during science measurement is 2 kbits/s.

The MLA laser is a diode pumped Nd:YAG slab laser with passive Q-switching. The laser output is 20 mJ/pulse at 8 Hz and 6 ns pulse width. The laser beam is TEM00 in far field pattern with a divergence angle of less than 80 µrad FWHM at the output of the 15X beam expander. The total mass of the laser without the beam expander is 0.56kg and the electrical power consumption is 8.7 Watts.

The MLA receiver consists of four 11cm diameter refractive telescope assemblies with a receiver field of view of 400 µrad FWHM. Four multimode optical fibers are used to couple the optical signal from the focal points of the telescope to a Si avalanche photodiode. A 0.7nm FWHM optical bandpass filter is included in the aft optics to minimize solar background light.

The MLA range measurement unit (RMU) employs a unique APL-supplied "Time-of-Flight" ASIC which uses on-chip signal propagation time to gauge the time interval between two pulses. It has the unique advantages of sub nanosecond (0.4ns) timing but without the need of high speed digital electronics. The RMU can time up to 15 pulses with less than 2 microseconds recovery time, which enables the receiver to lower its detection threshold to register a weak signal in the presence of several false alarm pulses. The on-board software algorithm rejects most of the false alarms and downlink only the likely signal to earth. The receiver is expected to range to beyond 1200 km for nadir pointing and 800 km for 50 degree off nadir pointing at Mercury.

MLA is currently on the spacecraft undergoing environmental testing at NASA GSFC. MESSENGER is on schedule for launch on July 30, 2004.

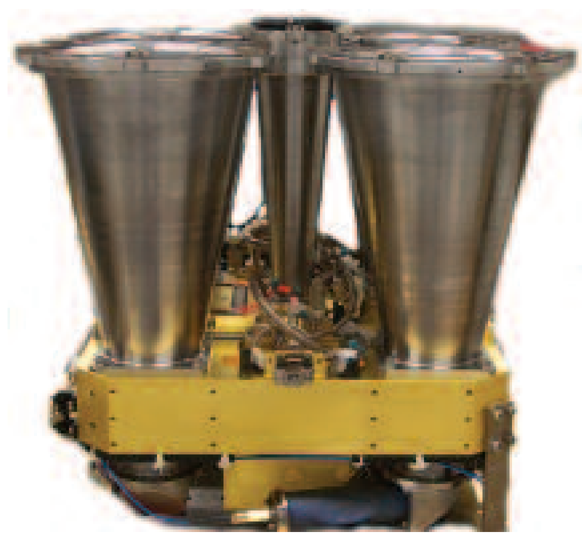

Figure 1. MLA in its handling fixture before delivering to APL.

Contact: Xiaoli Sun, Xiaoli.Sun-1@nasa.gov

Laser Sounder for Measuring Atmospheric CO_2 concentrations from Orbit

We are developing a laser-based sounding approach for remotely measuring the global concentration of atmospheric CO_2 from a satellite. In our method, CO_2 abundance is measured by using a 3 channel nadir viewing lidar in a 550 km altitude dawn/dusk orbit. The CO_2 measurement is made utilizing the strong laser echoes from the surface as the lasers are rapidly turned on and off a selected CO_2 line in the overtone band near 1570 nm. A similar technique is used simultaneously on a second channel to measure the surface pressure by utilizing a line in the oxygen A band near 770 nm. The dry-air mixing ratio can be calculated from the ratio of CO_2 to O_2, which can be measured using a similar technique applied to a line in the O_2 absorption band at 770 nm. A third channel operating at 1064 nm is used to detect and screen measurements influenced by cloud and aerosols in the path.

Our gas-sensing approach leverages laser diodes, erbium fiber amplifiers (EDFA's) and detector technology developed by the telecommunications industry, and by using available components, some of which already have been space qualified. Since gas absorption sensing precisions of < 0.5% are needed, both high signal-to-noise ratios and very stable components are required. Our approach also utilizes the strong laser echoes reflected from Earth's surface and thus senses gas in an integrated vertical column. However, the absorption measurement can be weighted to the lower troposphere as needed by exploiting pressure broadening and measuring to the side of the absorption line. In addition, a robust and stable calibration approach using several built in gas cells is required.

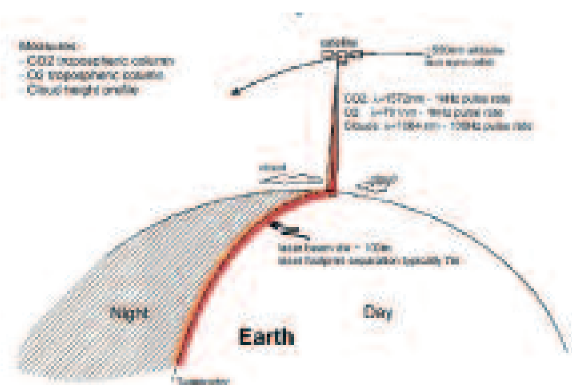

Figure 1. Laser Sounder Measurement Concept

In work to date, we have made many absorption line measurements using CO_2 both in an absorption cell and over an open atmospheric path. Figure 3 shows a line scan for gas in an absorption cell using a diode laser. Similar line scans have been made when the diode laser was amplified by an erbium-doped fiber amplifier (EDFA) to the 5W level. We have also made CO_2 measurements over an open 205 m horizontal path, and an example is shown in Figure 4.

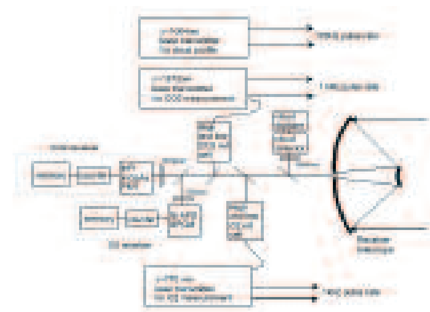

Figure 2. Laser Sounder instrument block diagram

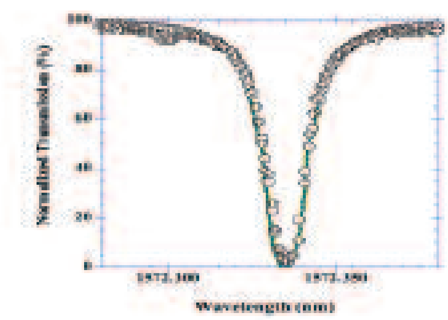

Figure 3. Scan of the CO_2 absorption line at 1572.34 nm using a tunable diode laser

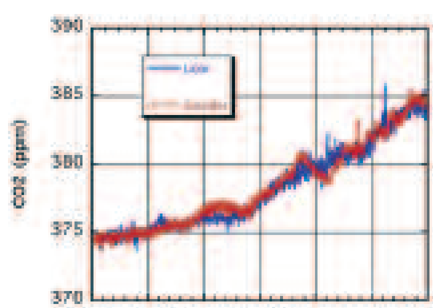

Figure 4. 6 hour long CO_2 measurement (red) series made with sounder breadboard over 205 m horizontal path, compared with Licor in-situ sensor readings (blue) sampled from roof of Goddard's Building 33.

Contact: Jim Abshire, James.B.Abshire@nasa.gov

The Space Lidar Technology Center (SLTC)

The Space Lidar Technology Center (SLTC) was established in 1997 under a Cooperative Agreement with the University of Maryland's James Clark School of Engineering. The purpose of the agreement provided a means for collaborating on lasers, opto-electronics, and material science related to instrumentation for space-based lidar.

The SLTC was used to develop the Geoscience Laser Altimeter System (GLAS), Fig. 1 and Mercury Laser Altimeter (MLA) flight lasers. This state-of-the-art facility was equipped with two cleanrooms, an ultra-clean vacuum chamber, a full size machine shop and several support laboratories for developing lasers and electro-optic components.

Figure 1. GLAS laser operating on optics bench

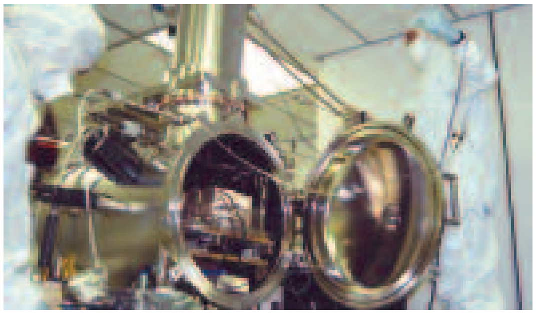

Figure 2. Thermal Vacuum Chamber at SLTC

With an immediate need to build flight-qualified lasers for space applications, the building was entirely remodeled and this state of the art facility was completed in only 4 months.

SLTC support labs included a thermal stress-relieving laboratory, where parts were processed as part of the fabrication process and two cleaning laboratories equipped with several ultrasonic baths, flow benches and a large size fume hood where parts underwent cleaning before being considered for use. The precision cleaning area was also equipped with a Thermal Vacuum Chamber, Fig. 2, and bake-out Vacuum ovens.

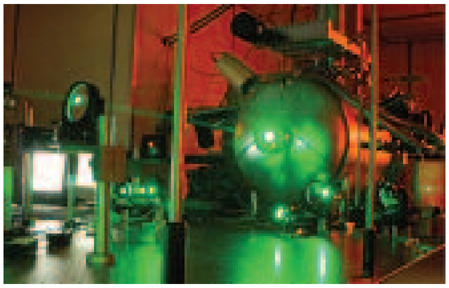

Figure 3. GLAS laser transmitter operating in thermal vacuum chamber

The 2000 ft2, class 1000 cleanroom was divided into an Assembly area and a Precision Cleaning area, Fig. 4 & 5.

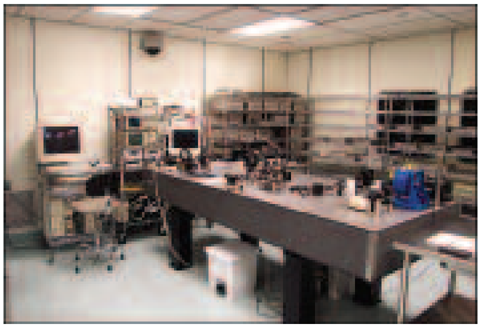

Figure 4. SLTC Assembly Clean room (1 of 3 Optical tables)

An impressive amount of effort was devoted to maintain this facility's cleanroom at peak performance and was considered one of Goddard's top clean rooms. The equipment and capabilities established at the SLTC were essential to the development and delivery of the GLAS and MLA laser transmitters. The capability of this facility has been moved from its off-center site, to the Earth Systems Science Building (ESSB).

Figure 5. SLTC Precision Cleaning Area

Contact: Pam Millar, Pamela.S.Millar@nasa.gov

The Laser Vegetation Imaging Sensor (LVIS): Large-scale mapping of vegetation vertical structure and bare-Earth topography

NASA's Laser Vegetation Imaging Sensor (LVIS) is a medium/high-altitude airborne scanning laser altimeter that generates true 3-dimensional volumetric maps of the surface of the Earth. LVIS utilizes a unique, waveform-based measurement scheme to produce precise and accurate images of topography and vegetation height, in addition to volumetric maps of vegetated surfaces. Data have been collected in various biomes around the world, including Panama, Costa Rica, California, and the eastern US. These data demonstrate that the system accurately measures bare-Earth topography and canopy height, even in dense, closed (99%) forest canopies. Numerous studies have shown the efficacy of the data for downstream scientific application including the estimation of aboveground biomass and forest parameters over large areas and under conditions where other remote sensing techniques have difficulty. The LVIS sensor is currently participating in studies for the North American Carbon Program and NASA's Solid Earth and Natural Hazards Program looking at topographic change detection. During the summer of 2003, LVIS mapped 2,000 km2 in Maryland and New England for vegetation and topography studies. An example of topography (Figure 1) and vegetation height (Figure 2) data extracted from the LVIS return waveforms from the Patapsco river area in Maryland is shown below. Data were also collected for the Howland Forest, Harvard Forest, the Bartlett Experimental Forest, Hubbard Brook Forest, Penobscot Forest, and the Smithsonian Environmental Research Center (SERC). Quicklook images of these data have been released and final processed versions will be released in the summer of 2004. The LVIS instrument continues to serve as a research platform for prototyping laser imaging techniques, real-time and data post-processing algorithms, and new science application and measurement concept development for future airborne and spaceborne laser altimeters.

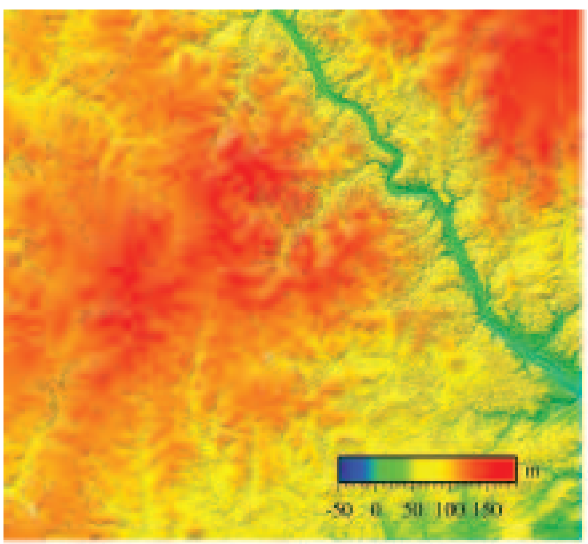

Figure 1. Bare-earth topography for an urban and forested region in central Maryland, collected in leaf-on conditions with the LVIS instrument. Elevations range from 0 to ~150 m above the WGS-84 ellipsoid.

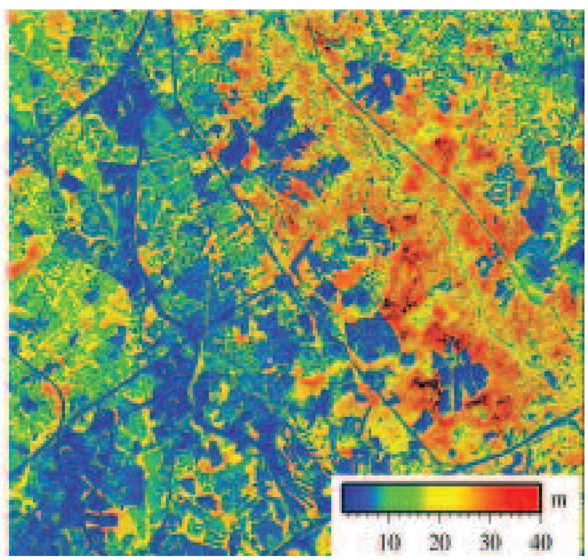

Figure 2. Vertical extent of vegetation and buildings in the same region of central Maryland. Blue areas are flat (ex. roads), and yellow and red areas are tree heights ranging from 20-35 m.

Contact: J. Bryan Blair, James.B.Blair@nasa.gov

Advanced Mapping Photon-counting LIDAR (AMPL)

Building on the heritage provided by the Multi-kilohertz Micro-Laser Altimeter (MMLA), an improved system known as the Advanced Mapping Photon-counting LIDAR (AMPL) is under development at Goddard. The objectives of this effort are to implement a fully-functional, photon-counting, imaging lidar capability for surface elevation mapping and to acquire data for priority land, vegetation, snow/ice, and water targets in order to assess the measurement capability and information retrieval. The instrument will simultaneously acquire surface altimetry and atmospheric profiling data, be configured for autonomous operation at high airborne altitudes, and be appropriate for implementation in orbit as a Shuttle Small Payload Project Hitchhiker Experiment, following in the series of Shuttle Laser Altimeter experiments when future opportunities for shuttle manifesting arise.

The implementation includes reuse of some MMLA infrastructure, including the optical bench, scanner, and 4 x 4 pixelated photon-counting detector. Instrument upgrades focus on the receiver electronics and laser transmitter. A space-qualifiable, multi-event timer card capable of operating at laser fire rates up to 100 kHz has been developed to achieve unlimited photon hits per pixel with 10 nsec deadtime (1.5 m) and 1 nsec timing resolution (15 cm), suitable for detection of multiple reflections from vegetation canopy and underlying ground. An advanced multi-channel scaler provides pulse counting, integration, and histogramming functions enabling atmospheric lidar profiling and surface return range gate generation. The fiber-coupled, solid-state diode, 512 nm laser transmitter is optimized for photon counting link margins in low Earth orbit. It is designed to operate at 1.2 kHz with 4 mJ per pulse and the sub-nsec pulsewidth, the limiting factor in range precision, is matched to the timing resolution.

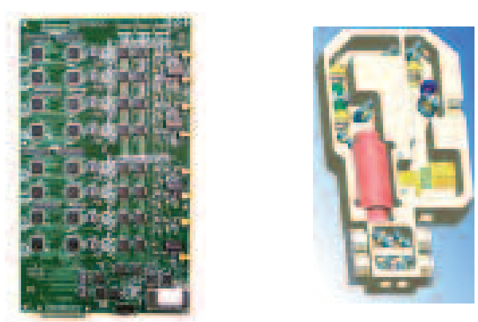

Figure 1. Multi-event timer card (left) and schematic of the fiber-coupled laser transmitter (right).

Airborne operations are planned in 2004 aboard the high-altitude Proteus aircraft based at Dryden Flight Facility. Although currently piloted, the Proteus is intended to be an unmanned aerial vehicle, providing opportunities for long duration missions. AMPL will be installed in a Proteus instrument pod developed by Langley Research Center and will serve as a development testbed, for testing miniaturized electronic and optical components suitable for spaceflight instrument designs. Proposed miniaturization efforts include a reconfigurable FPGA-based data system on a chip, a compact and low power 10x10 detector array system, and a dual-wedge optical scanner.

Figure 2. Proteus aircraft with instrument pod beneath the fuselage.

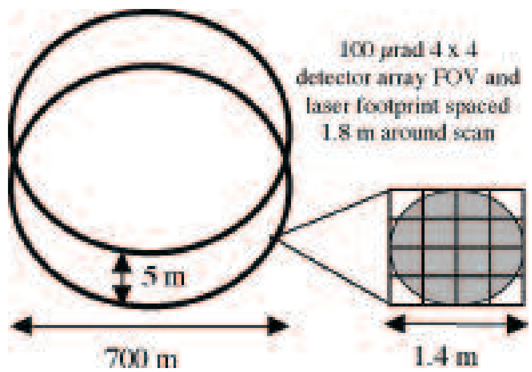

Figure 3. Nominal measurement geometry for 20 km altitude, 100 m/sec ground speed, 1.2 kHz laser rep rate, and 20 Hz 2° circular scan. Options to more fully sample the swath along track are being evaluated, including a counter-rotating dual-wedge scanner and wider FOV and beam divergence.

Contact: Phil Dabney, Philip.W.Dabney@nasa.gov

Spectral Ratio Biospheric Lidar

The Normalized Difference Vegetation Index (NDVI) and related vegetation indices (VI) rely on the distinctive optical properties (reflectivity and absorption) of chlorophyll containing vegetation. The dominant pigment in plant leaves, Chl a, strongly absorbs visible light (from 0.4 to 0.7 µm) for use in photosynthesis, with blue and red peaks near 0.43 and 0.67 µm. However, the cell structure of the leaves strongly reflects near-infrared light (from 0.7 to 1.2 µm). This transition around 0.7 µm is referred to as the red edge, Fig. 1. In general, if there is much less reflected radiation in red wavelengths than in near-infrared wavelengths, then the vegetation is likely healthy and dense whereas if there is little difference in the intensity of the reflected red and near-infrared wavelengths then plant leaves are likely sparse, absent, or dead.

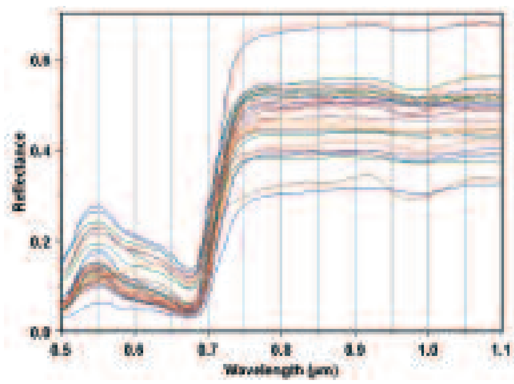

Figure 1. Spectral reflectance of chlorophyll containing vegetation.

A laboratory instrument using diode lasers, 203 mm diameter telescope, and photon counting detectors was developed in 2002-2003. This instrument was used during the Fall 2003 to demonstrate the feasibility of the underlying measurement concept, namely the ability to quantify the spectral reflectance of changing vegetation, i.e., deciduous trees changing color and dropping their foliage. The system specifications of the instrument are listed in Table 1.

Table 1. System Specifications.

Item	**Red**	**NIR**
Laser	Hitachi HL 6501	Sanyo DL7140
Laser Power	30 mW	70 MW
Wavelength Beam splitter -45º	660 +/- 5 nm R>95% @ 658.5 nm	780 +/- 5 nm T>90% @ 781.0
Dichroic Bandpass Filter 0.3	T<0.01 658.5 +/- 0.1 nm	nm 781.0 +/- 0.2 nm
nm FWHM Detectors EG&G	SPCM-AQR-13-FC	same

Contact: Jonathan Rall, jonathan.a.rall@nasa.gov

The instrument was operated horizontally over several hundred meters to a stand of deciduous trees. Measurements were made approximately once per week from October through November. Fig. 3 shows the ratio of the reflected NIR signal to the Red signal.

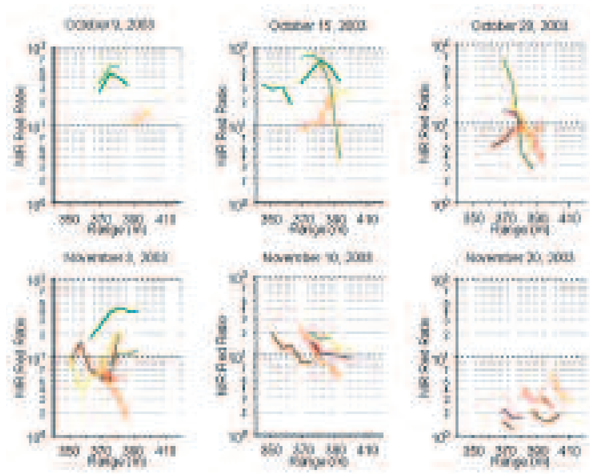

Figure 3. Spectral ratio measurements of deciduous trees.

Initial reflectance ratios of 40-50, indicating healthy, green vegetation, are evident from the measurements taken on 10/9/03. As time progresses and the vegetation loses chlorophyll content, the reflectance ratio drops and eventually settles at a ratio of around 2-2.5 which is roughly equivalent to the ratio of the outgoing NIR/Red laser transmitter power.

With the success of the low power demonstration system, we are moving forward with developing higher power laser sources. There are currently no space-qualified, high power lasers available at 660 nm & 780 nm. The current approach for scaling transmitter power at these wavelengths for high-altitude airborne and spaceborne applications is to use rare-earth-doped fiber amplifiers and Raman amplifiers to generate 1.56 µm and 1.32 µm respectively. Through efficient, quasi phase-matched frequency doubling we expect to achieve several watts at 780 nm and 660 nm, respectively.

CO_2 Boundary Layer Profiler

The CO_2 profiler is a prototype Differential Absorption Lidar (DIAL) designed to profile CO_2 within the planetary boundary layer at high vertical resolution (15-150 meters) with a precision of < 1 ppmv. It is designed to identify and quantify terrestrial sources and sinks for CO_2. Anticipated enhancements to both detectors and lasers will extend its capabilities into the free troposphere and enable satellite validation of future instruments making column measurements of CO_2 – e.g. the Orbiting Carbon Observatory (OCO). The profiler leverages and complements GSFC efforts to develop a space-based CO_2 laser sounder. Both the (distributed feedback) DFB lasers (used to generate the on and offline wavelengths) and the erbium doped fiber amplifier (EDFA) are commercial products that have been rigorously tested by the telecommunications industry.

The profiler derives CO_2 concentration as a function of altitude by using two wavelengths – one strongly absorbed by CO_2while the second wavelength is not absorbed. Because the two wavelengths are separated by only ~0.15 nm, other sources of signal extinction (aerosol scattering) will have an identical impact at both wavelengths.

The proposed on-line wavelength at 1570.8 nm has both a large absorption cross section and minimal impact from expected temperature changes within the boundary layer. Unlike the 2.05-micron region being used by other active CO_2 instruments, there is no spectral interference by water vapor. Signals will be generated by using backscattering from boundary layer aerosols. Time series data acquired by the GSFC Micro-Pulse Lidar demonstrates that the expected returns will permit daytime profiling to the top of the summer boundary layer (~3 km AGL).

As with the sounder a channel to provide a measurement of O_2 will be included to permit the derivation of the dry air CO_2 mixing ratio. Unlike the sounder extremely short pulses are required to provide the desired range resolution (15-150 meters). An acusto optic modulator will be employed to generate the short pulses that will then be amplified in an EDFA amplifier. Pulse repetition rates of between 10-100 kHz will be used which will effectively limit the impact of atmospheric motion on the retrieval.

We have demonstrated real time line locking of both DFB lasers with a wavelength uncertainty of <0.1 pm – the precision of the wave meter used in this experiment (Fig.1). This minimizes a major source of uncertainty for the CO_2 measurement to less than 1 part in 1000.

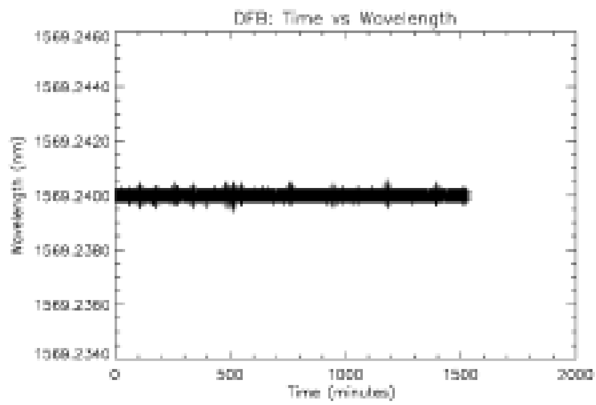

Figure 1. DFB laser wavelength locked to better than 0.1 pm over a 25 hour period

Contact: John Burris, John.F.Burris@nasa.gov

Atmospheric Pressure Sounder

The long-term goal of this research is to demonstrate the feasibility of a laser sounder instrument capable of measuring the surface-pressure field for the entire air column from satellite-to-ground with global coverage. The Earth's surface pressure is a vital component of a variety of important scientific measurements, which are being undertaken at Goddard. Accurate knowledge of the surface pressure can enable calibration of 2-D measurements of CO_2 content in the atmosphere and greatly improve the fidelity of surface water redistribution measurements from time-varying gravity fields. It is also important in weather prediction and atmospheric modeling. The measurement approach uses differential absorption spectroscopy of O_2 in the 770 nm wavelength region to derive atmospheric pressure. The planned instrument architecture would be a nadir-viewing laser instrument that analyzes the ground reflections from the Earth. Applying DIAL to the oxygen absorption for monitoring pressure was pioneered at Goddard by Korb, et al. In contrast to previous laser-based instruments for this application, our laser sounder instrument leverages telecommunication laser-diode and fiber-optic amplifier technology that is low-cost, high power, high efficiency, high reliability and robust. This technology allows a direct instrument development pathway to space flight deployment. Using the 770 nm oxygen feature in the peak of the silicon absorption for photo-detectors means we can use state-of-the-art, high quantum efficiency, photon counting receivers with spaceflight heritage like those used on the ICESat mission.

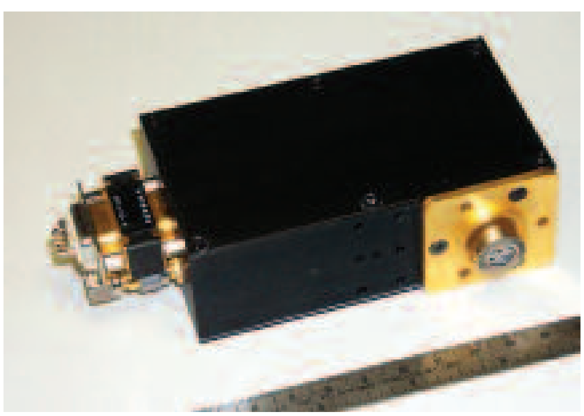

Figure 1. Single Photon Counting Module (SPCM) made by Perkin Elmer for ICESat Mission.

In addition, the active laser sounding technique has advantages over passive spectrometers in its high (MHz) spectral resolution and stability, the ability to measure at night and in daytime, a narrow measurement swath, and the ability to simultaneously detect and exclude measurements with clouds or aerosols in the path. O_2 absorption lines are free from contamination from other gases and are within the tuning range of lasers. When averaging over 50 seconds, calculations show a SNR of > 1000 appears achievable for each on- and off-line measurement. Such a mission can furnish global maps of the lower tropospheric O_2 column abundance at dawn and dusk. Global coverage with an accuracy of a few mbar appears achievable.

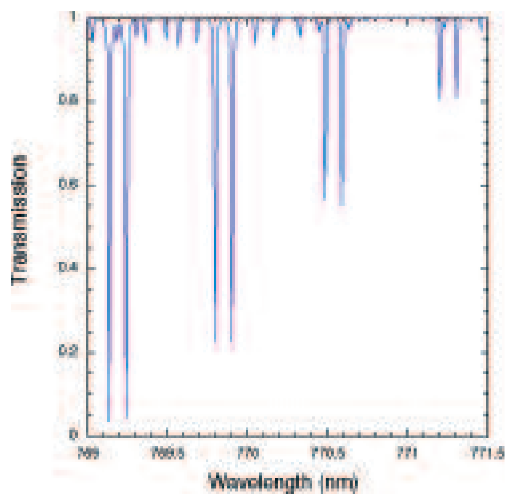

Figure 2. HITRAN calculation of ground-space absorption for candidate O_2 lines.

To demonstrate the feasibility of this instrument design, we will first characterize and optimize the laser transmitter for this application. Our transmitter consists of a fiber coupled, tunable, 1540 nm, DFB laser diode, amplified by an erbium-doped fiber amplifier (EDFA) and then frequency doubled to 770 nm. We are currently exploring the limits of power, pulse width, duty cycle, and spectral width and stability for different EDFAs. We will then optimize the frequency conversion efficiency. This technology development can also be applied to two-color frequency doubled systems for a normalized difference vegetation index lidar instrument. Once the laser transmitter has been demonstrated, it will be integrated into a laboratory-based laser sounding instrument to make oxygen measurements. The lab-based instrument is capable of measuring oxygen content in both a gas cell and a 300-meter atmospheric path. This allows us to fully calibrate the measurements as well as test the instrument capability in the atmosphere.

Contact: Mark Stephen, Mark.A.Stephen@nasa.gov

High Repetition Rate Laser Development for High Density Topographical and Vegetation Mapping

Recent developments in laser-based altimeters have been in the direction of reduced size, higher pulse repetition frequencies (PRFs), and smaller footprints. Assorted atmospheric lidars are also employing small, high repetition rate solid state lasers instead of the usual joule-level pulsed systems. Partly funded through the Director's Discretionary Fund (DDF) awards and remainder efforts under the Laser Risk Reduction Program, we have vigorously studied promising methods in achieving higher PRFs from somewhat standard Nd:YAG laser designs and new methods of diode pumped, doped fiber amplifiers. The Nd:YAG laser systems under development are variations on small 10– 25 cm cavities, end-pumped rods or side-pumped slabs, and actively Q-switched. Passive Q-switching may have advantages in its lack of high voltages and timing electronics, but the ≥ 30% hit in laser efficiency and lack of adjustability for optimization makes it worth the extra effort to use electro-optic methods. Furthermore, there are new electro-optic materials on the market promising 1/3 – 1/5 the driving voltages of standard KD*P Q-switches. Thus, with any hopes of driving a laser’s electrical/optical efficiency above 2-3%, active Q-switching methods must be used.

To date, we have demonstrated optical efficiencies as high as 14% with single spatial mode and 6 ns – 10 ns pulse widths. PRFs were run as high as 300 Hz while maintaining good beam quality with intracavity optics to counter the strengthening thermal lensing effects in the Nd:YAG crystals. Immediate plans include driving the PRFs up to 1 kHz when new diode arrays are mounted and tested. By driving more diodes at shorter pulses, the laser efficiencies are actually improved due to the reduced effects of spontaneous emission.

Figure 1. Typical cavity studied for high PRF work.

For PRFs in the kHz regime, the most efficient means to produce laser pulses on the order of 2-10 ns and 1.0-1.1 µm in wavelength are with seeded pulsed fiber amplifiers. We are pursuing, and have demonstrated, a 1 W average power fiber amplifier seeded with a single frequency pulse. A custom diode laser tuned with a KTP chip with an imbedded Bragg grating produces the seed pulse. Work is underway to provide over 100 mW of seed power, and pulse pump the amplifier to increase the gains from 20 dB to over 50 dB. Our seed diode, shown in Figure 2, is being upgraded from a 10 mW design to a unit which will produce up to 200 mW peak power or greater. This proof of concept supports the ability now to produce a compact, efficient laser transmitter which can be completely tunable in pulse width, pulse shape, PRF and pulse energy.

To date, this is not possible with any non-diode only technique with these energies and wavelengths. Included in this seeded amplifier system is a 5 W diode at 980 nm which pumps the fiber amplifier. This diode is pulsed in the 100 µs regime and fiber coupled into the Yb:Fiber for gain production. When operated in CW mode, this system typically produces approximately 20% electrical/optical efficiencies. In pulsed mode, the efficiency will be somewhat lower, but still many times that of a diode pumped Nd:YAG or Nd:YLF oscillator/amplifier laser design. With proper drive electronics and new, amplifier designs optimized for pulse pumping, the efficiencies should reach the CW numbers, and possibly exceed them.

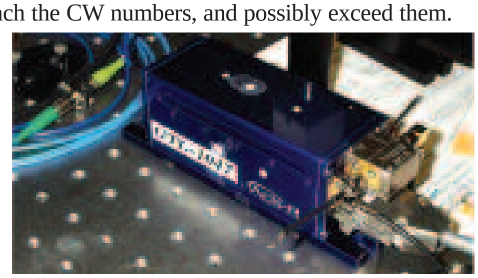

Figure 2. 1047 nm diode seeder, fiber coupled and injected into a diode pumped Yb:fiber amplifier for gains of 30 dB.

Immediate plans for this high PRF system is to repackage and fly on a NASA aircraft as part of the Laser Vegetation Imaging System (LVIS) instrument as a technology demonstration for high density earth mapping. Furthermore, a new custom seeder/fiber amp combination is under design for optimum performance under these new conditions. A patent application has been submitted in early 2004 for this laser pulse generation concept.

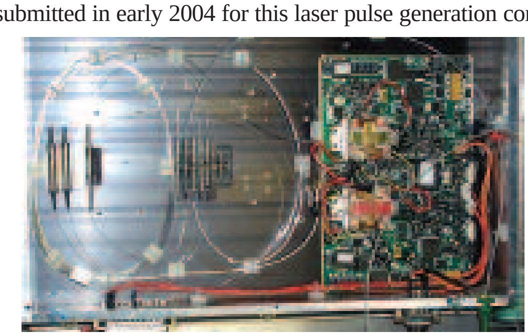

Figure 3. CW pumped, 10 -100 kHz seeded fiber amplifier producing average powers up to 1.2 W.

Contact: Barry Coyle, Donald.B.Coyle@nasa.gov

Laser Risk Reduction Research for Improving Laser Transmitter Reliabilities for Space Based Applications

During the course of this research under the Laser Risk Reduction Program (LRRP), solid-state laser oscillator architectures are continually reviewed, studied, and improved. New laser modeling techniques are evaluated, mastered and added to current models. Designs are evaluated for various missions, literature searches are performed, new oscillator designs advanced, breadboard models built and evaluated, and promising schemes constructed and seeded. Additionally, small amplifiers are being designed and tested. Our focus is mostly centered on improvements in efficiency, increased average powers, and damage-free operation. Any technologies that can directly affect these parameters are immediate candidates for study.

Specifically, the 2003 efforts concentrated on 4 applications for modeling refinements. These 4 projects were a small sub-10 mJ oscillator design, a larger 10-20 mJ laser oscillator, a compact high gain pre-amplification, and the packaging and long term testing of our 10–20 mJ oscillator. Of particular interest is the small amplifier work. Our new design enables a single-pass gain path length of over 18 cm in a crystal only 2 cm x 0.75 cm in size. Shown from above in Figure 1, when side pumped with diode arrays, the "Coffin" slab design is already demonstrating that stored energy extraction efficiencies should approach the theoretical limit once some component improvements are made. This crystal shape is dubbed the "Coffin" due to its stretched hexagonal geometry. Much work still needs to be done with optimizing the pump beam profile, the injection beam quality, and negotiating the thermal lensing effects which will surely arise when average powers are increased. However, it has already demonstrated remarkable performance prior to any planned improvements.

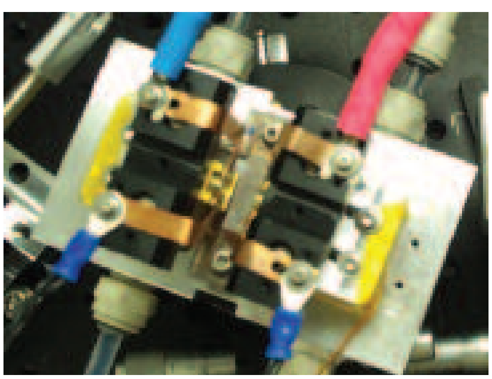

Figure 1. The "Coffin" amplifier slab has already demonstrated remarkable efficiencies due to its long internal path length.

The mid-range oscillator was the most progressed in 2003, partly due to the Vegetation Canopy Lidar (VCL) experience. Code 920's assumption of laser development from an outside contractor in VCL's mid-mission, and the successful completion of a 5 billion shot life test experiment with the 15 mJ oscillator, fostered the result shown in Figure 2. This has been renamed the High Output Maximum Efficiency Resonator (HOMER) and is our new candidate design for the next vegetation or Earth mapping mission to be proposed. A new prototype package design has been completed and the first unit is under fabrication as of this writing. This unit will begin immediate long term testing to add to the existing life test. Two or more improved copies will be made for vacuum alignment testing, benchtop thermal cycling, external single frequency seed research, and ultimately even more extensive multibillion shot power cycled life testing. The electrical connections for pump diode power, temperature sensors and Q-switch timing and other logic are located below the base plate. Furthermore, the unit is passively conductively cooled via bolting a radiator, heat pipe, or large thermal sink underneath the laser head location. The lack of circulating liquid, typical of lasers of this average power, is important for candidacy for eventual space flight.

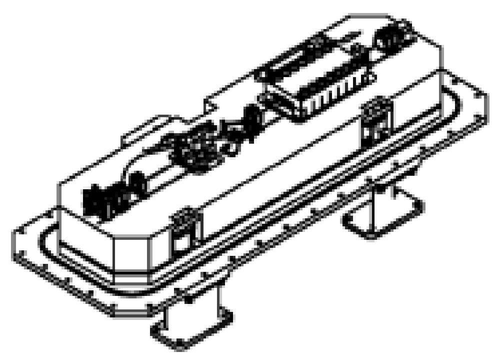

Figure 2. Prototype HOMER laser. Optical bench and base plate. (Output:10 – 20 mJ, 100 – 300 Hz, 9 – 11 ns, 1064 nm)

One more spinoff from the LRRP effort has been the commercialization of a new data system based on Apple's OSX platform for real-time optical and laser technology development. This is important because no such product exists for the Macintosh platform. Furthermore, the new data system was contracted to our specifications by a small local software company. Significant improvements and new capabilities were included where other PC-based data systems, similar in application, were lacking. Thus, we hope to have fostered a new software/hardware package in the laser R&D marketplace during 2004.

Contact: Barry Coyle, Donald.B.Coyle@nasa.gov

Photon counting detectors for the 1.0 - 2.0 µm wavelength range

The purpose of this effort under the Goddard Laser Risk Reduction Program is to improve 1.0 - 2.0 µm wavelength laser instrument system margins by improving the detector sensitivity. The advantages of receiver improvements include equivalence to laser power/energy improvements for most LIDAR applications; low negative system impacts (i.e., little increase in thermal load, weight, power); application to a wide range of laser technologies, and operation beyond the retinal thermal damage wavelengths above 1.4 µm (i.e., "eye-safe").

The technical goals include quantum efficiency in the range 10 - 70%, detector diameter above 200 µm, dark count rate below 100 kcps, and maximum count rate above 10 Mcps.

The baseline device is a commercial photomultiplier tube made by Hamamatsu. Its device characteristics have been measured as 3mm x 8mm detector size; 4% quantum efficiency @ 1572 nm; gain 10^6 at 1.5 kV, and dark count rate 300 kcps @ 193 K. The Hamamatsu PMT has lifetime limitations for continuously operating lidar applications. Our near term goal is to demonstrate the use of this device in the Laser Sounder for atmospheric CO_2 and CO_2 profiler instruments.

We are investigating three new approaches for high quantum efficiency photon counting detectors in the 1.0 - 2.0 µm wavelength range. All of these rely on solid state indium gallium arsenide (InGaAs) epitaxy technology. The approaches are: 1) cooled (190 K) InGaAs-InAlAs avalanche photodiodes (APDs), 2) cooled (190 K) InGaAs-Si APDs and 3) InGaAs photocathode hybrid PMTs. The major effort has been the design, build and test of hardware and software for a photon counting detector test station and initial tests of InGaAs-InAlAs devices.

Figure 1 shows an average photon count for the 75 micron diameter InGaAs-InAlAs APD. The rise time (< 3 ns) is limited by the post amplifier bandwidth and the fall time is limited by the passive quenching circuit. Figure 2 shows the linearity and dynamic range of the 75 µm diameter InGaAs-InAlAs APD.

Future work includes measuring the photon counting performance of the larger diameter APDs, the quantum efficiency (typically 1- 10% in similar devices tested by others) and detector total count, time internal, and multiplication process statistics.

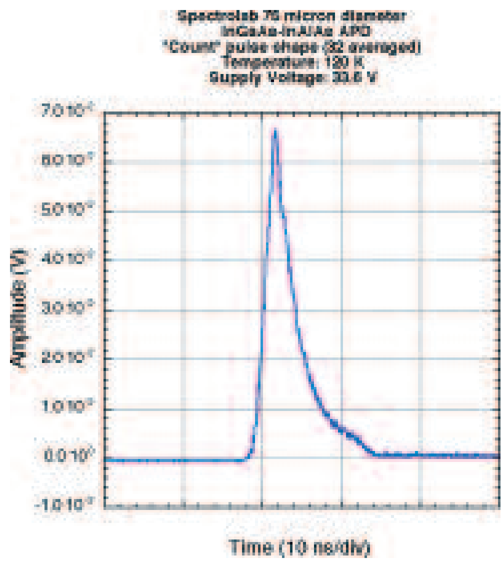

Figure 1. Average photon count from InGaAs-InAlAs APD. operating at 120 K temperature.

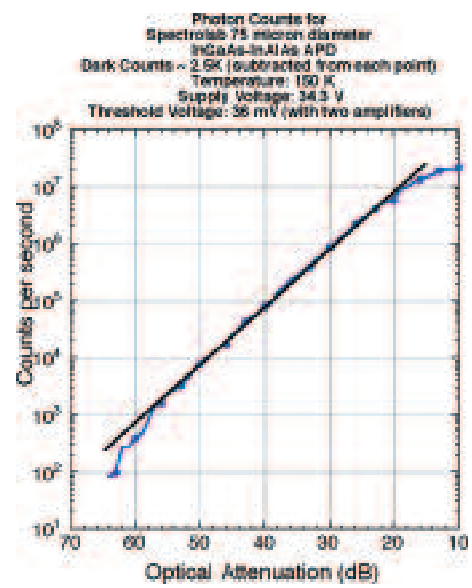

Figure 2. Linearity and dynamic range of photon counting InGaAs-InAlAs APD operating at 150 K temperature.

Contact: Michael A. Krainak, Michael.A.Krainak@nasa.gov

NASA Satellite Laser Ranging (SLR) Network

Satellite Laser Ranging (SLR) is a fundamental measurement technique used by the NASA Space Geodesy Program to support both national and international programs in Earth dynamics, ocean and ice surface altimetry, navigation and positioning, and technology development. NASA continues to maintain and operate five trailer-based Mobile Laser Ranging Stations (MOBLAS) and two compact Transportable Laser Ranging Systems (TLRS) at fixed sites. The University of Hawaii and the University of Texas continues to operate the two high performing Observatory SLR systems at their respective Universities with the University of Texas system having lunar ranging capability. NASA has continued its successful partnerships with Geoscience Australia, formerly the Australian Surveying & Land Information Group (AUSLIG), in Yarragadee, Australia (MOBLAS-5); the South African National Research Foundation Hartelbeesthoek Radio Astronomical Observatory (HRAO) in Hartelbeesthoek, South Africa (MOBLAS-6); and the University of French Polynesia/CNES installation in Tahiti, French Polynesia (MOBLAS-8).

Overall, the NASA Network consists of nine NASA-operated, partner-operated or University-operated stations covering North America, the west coast of South America, the Pacific, South Africa, and Western Australia. The NASA SLR Network continues to provide over 40% of the total data volume in the International Laser Ranging Service (ILRS) as well as the most precise sub-cm accuracy ranging data.

Location	SLR System	Operating Agency
Monument Peak, California	MOBLAS-4	Mission Contractor (HTSI)
Greenbelt, Maryland	MOBLAS-7	Mission Contractor (HTSI)
Mount Haleakala, Maui, Hawaii	HOLLAS	University of Hawaii
Fort Davis, Texas	MLRS	University of Texas at Austin
Arequipa, Peru	TLRS-3	Universidad Nacional de San Agustin
Yarragadee, Australia	MOBLAS-5	Australian Surveying & Land Information Group
Hartebeesthoek, South Africa	MOBLAS-6	National Research Foundation
Tahiti, French Polynesia	MOBLAS-8	University of French Polynesia/CNES
Greenbelt, Maryland*	TLRS-4	Mission Contractor (HTSI)

* System not in operational status

Contact: David Carter, David.L.Carter@nasa.gov

International Laser Ranging Service (ILRS)

The ILRS was established in 1998 as an official service of the International Association for Geodesy (IAG). The ILRS collects, merges, analyzes, archives, and distributes Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) observation data sets of sufficient accuracy to satisfy the objectives of a wide range of scientific, engineering, and operational applications and experimentation. The basic observable is the precise time-of-flight of an ultrashort laser pulse to and from a satellite, corrected for atmospheric delays. These data sets are used by the ILRS to generate a number of fundamental data products, including: centimeter accuracy satellite ephemerides, Earth orientation parameters, three-dimensional coordinates and velocities of the ILRS tracking stations, time-varying geocenter coordinates, static and time-varying coefficients of the Earth's gravity field, fundamental physical constants, lunar ephemerides and librations, and lunar orientation parameters. As such, the ILRS provides fundamental data to support the International Terrestrial Reference Frame (ITRF) and the International Earth Rotation and Reference Systems Service (IERS). The ILRS consists of several operational elements: tracking stations, operational centers, analysis centers, data centers, and a central bureau.

ILRS Network and Satellite Missions

By the end of 2003, the ILRS network of 42 stations, shown in the figure below, routinely tracked nearly thirty satellites (including passive geodetic satellites, Earth remote sensing satellites, navigation satellites, engineering missions) and the Moon, supporting a variety of scientific activities. Normal point data from nearly 100K satellite passes were archived at the ILRS data centers in 2003.

Figure 1. ILRS Network

Working Group Activities

The ILRS has established five Working Groups to help formulate policy and provide technical expertise. During 2003, the Missions Working Group, which reviews tracking priorities and develops recommendations for new requests for tracking, coordinated support for ADEOS-II (environmental monitoring), Reflector (satellite dynamics), and ICESat (altimetry). In 2003, the Data Formats and Procedures Working Group reviewed data integrity monitoring software. This working group continues to sponsor two study groups, one on determining necessary modifications to the current satellite predictions format and a second on atmospheric refraction models used in SLR analysis. The Networks and Engineering Working Group completed work on gathering system information into consistent site-specific log files for use by the analysis community. The Analysis Working Group held two workshops in 2003. These meetings focused on benchmarking and pilot projects designed to assess the current state of the SLR analysis community and eventually develop standard ILRS products such as daily X/Y pole and length-of-day values for the IERS. During 2003, the Signal Processing Ad Hoc Working Group continued to work on improved center-of-mass corrections and signal processing techniques for the many satellites currently tracked by SLR.

Meetings and Publications

The 9th ILRS General Assembly was held in Nice in April 2003 in conjunction with a Joint EGS-AGU-EGU meeting. The ILRS also held a technical workshop in October in Koetzting, Germany to examine how the service could work more effectively toward achieving the full potential of the SLR capability. The ILRS co-sponsored a meeting in Matera, Italy with the IERS. This workshop was devoted to site co-location survey objectives, methods, and issues. The quality of station coordinate results from the various space geodetic techniques is in the order of a few millimeters. In view of this precision, one of the major limiting factors in the establishment of a unique, high-precision terrestrial reference frame is the quality and availability of accurate local tie information for all the co-located sites around the globe. This workshop addressed some of the concerns in these co-location surveys and developed recommendations for future site surveys.

The 2001 ILRS Annual Report was published last year and a draft of the 2002 report was completed. The proceedings from the 13th International Workshop on Laser Ranging were published, including a CD of presentation material and resulting papers.

ILRS Website

The ILRS website (http://ilrs.gsfc.nasa.gov), hosted at NASA GSFC, underwent a significant redesign in 2003. A new navigation scheme was implemented with modifications to comply with mandated NASA and GSFC web guidelines. The ILRS network section of the site was greatly enhanced to provide performance information and easier access to site logs.

Contact: Carey Noll, Carey.E.Noll@nasa.gov

SLR2000 Autonomous Satellite Laser Ranging Station

The NASA Satellite Laser Ranging (SLR) network is scheduled to be replaced by a network of SLR2000 systems similar to the one currently under prototype development at the Goddard Geophysical and Astronomical Observatory (GGAO) in Greenbelt, Maryland. The SLR2000 is intended to be an autonomous, eye-safe, sub-centimeter precision ranging instrument capable of tracking a wide range of cube corner equipped satellites up to 20,000 km altitude. Pictured in Figure 1 is the SLR2000 prototype in operation.

Figure 1. Nighttime SLR2000 operation at the GGAO.

The SLR2000 system fires at a 2 KHz rate with a much reduced laser energy than the current tracking systems. Single photon detection in the receiver assures maximum utilization of all return photons. Current NASA SLR systems operate with a single laser pulse in flight and directly measure the roundtrip time-of-flight. Because of the high repetition fire rate of the SLR2000, tens to hundreds of laser shots are in flight at any instant. Hardware and software accommodates multiple shots in flight by time tagging with the system event timer all start and stop events, and establishing appropriate range windows for the optical receiver with the range gate generator. The SLR2000 is eye-safe when operated with a pulse energy of 135 μJ spread over the 40 cm telescope exit aperture; therefore, no mount safety observer or radar for aircraft avoidance is required. Autonomous operation requires a "smart" meteorological station which monitors wind speed and direction, air pressure, temperature, humidity, precipitation, visibility and sky cloud cover. Enabling technologies developed for the SLR2000 include: a unique polarization transmit/receive switch which enables the telescope to be used for both transmit and receive functions, a newly developed quadrant microchannel plate PMT which doubles as the range receiver and closed loop quadrant tracking device, a thermal IR all-sky cloud camera, and a Risley prism pair point ahead mechanism which fine steers the laser transmit beam ahead of the target.

Contact: Tom Zagwodzki, tom.zagwodzki@gsfc.nasa.gov

Visual tracking of sunlit satellites has been performed to verify the system's ability to accurately track. The sunlit satellite images were recorded using a CCD camera located on the optical bench. The field of view of the 242 x 242 pixel CCD is 120 arc minutes. Although the laser was not firing during these tests the telescope was still pointed ahead in the orbit to the location where the satellite would be when the laser pulse arrived. The offset of the image from the center of the CCD field of view is therefore the difference between the point-behind angle of the sunlight coming back from the satellite and the point-ahead angle of the telescope, biased by the off-pointing induced by mount model errors and any errors in calculating the image centroid. Figure 2 shows the measured offset of the image centroid from the center of the field of view plotted with the theoretical calculation of point-ahead minus point-behind for a Topex pass taken on January 8, 2004. The azimuth measured offsets were well within the ± 0.5 millidegree mount model azimuth errors. The elevation measured offsets were within the ±1.0 millidegree mount model elevation errors except at the lower elevations. This small discrepancy is believed to be a problem in the elevation mount model and warrants further investigation. However, the general conclusion from this plot and other sunlit passes is that the system's tracking ability is very good.

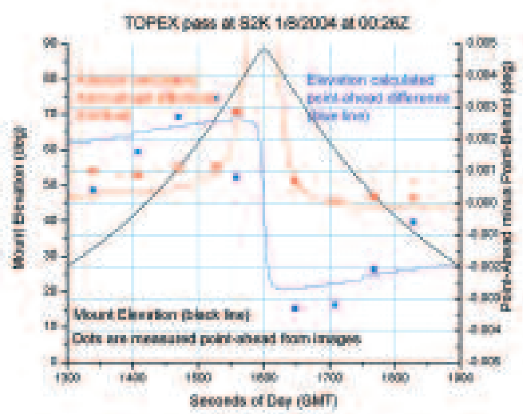

Figure 2. Predicted/observed point ahead/behind

The first SLR2000 satellite ranging results are expected in early CY04. Several months of system validation in co-location with NASA's SLR standard MOBLAS 7 are planned for the fall of 2004.

Radiometric Calibration Facility Activities

The Code 924 Radiometric Calibration Facility (RCF, http://cf.gsfc.nasa.gov) provides several uniform large-aperture (25.4+ cm diameter) sources of spectral radiance with NIST-traceable calibrations for use in the characterization and calibration of spaceborne, airborne, field, and laboratory instruments. Source calibrations cover the wavelength range of 0.4–2.4µm (violet through short wave infra-red.) Four large sources (1.8m, 1.4m, 1.2m, 1m diameter) are available, each of which can be stepped to one of sixteen intensity levels for simulation of dark scenes such as sunlit sea surface, bright scenes such as sunlit cloud tops, and higher intensities for solar instrument calibration. Several smaller sources (30-45 cm diameter) are also available. The maximum intensity emission spectra of the main RCF sources are shown in Figure 2 together with two comparison spectra. Most RCF sources are deployable for field calibration of customer instruments. Additionally, RCF staff and calibration transfer instruments are available for on-site or in-situ calibration of customer sources.

Typical of RCF sources, the 1.8m sphere 'Hardy' (Figure 1) is internally illuminated by a ring of quartz tungsten halogen lamps located just behind the wire harness. A suite of constant current DC power supplies drives the lamps, with a feedback control program stabilizing power levels to better than ± 0.01%. The interior is coated with barium sulfate in a polyvinyl-alcohol binder. This material is highly reflecting at wavelengths below 1 µm, resulting in a large number of diffuse reflections for those photons emitted from the lamp filaments exiting the source aperture. Consequently, spectral radiance uniformity across the 25 cm diameter exit aperture is better than ± 0.2% for wavelengths below 1 µm, and is almost as uniform at higher wavelengths. Unique to this source is a thermal control system to cool and dehumidify the sphere internal environment and continuous temperature and humidity monitoring.

Primary RCF sources are calibrated approximately every month relative to a NIST standard irradiance lamp. Secondary sources are calibrated as required. This procedure is necessary to offset slow degradation in radiance output caused by aging of the lamps and interior coating (usually a few percent per annum). Residual uncertainty in source spectral radiance is within the range ±1-2% (k=1), depending on the wavelength.

The RCF is developing a tunable laser based source for measurement of sensor system spectral response, system spectral radiance response, and single pixel illumination of arrays. The design is similar to that of NIST's SIRCUS facility.

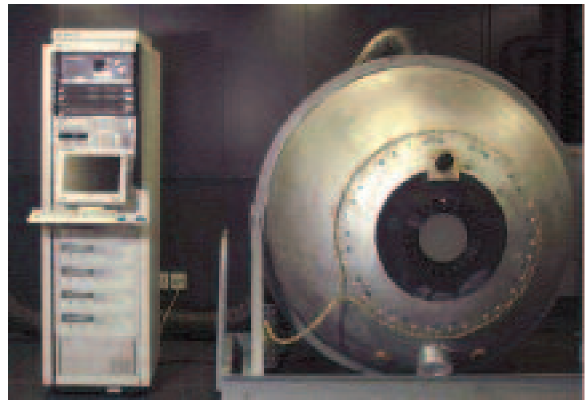

Figure 1. The 1.8 m diameter "Hardy" source with its power supply and data system console. The source aperture, defined by the circle within the black circle on the sphere, is 25.4 cm diameter. Not shown is the thermal control system.

Although the primary customers of the RCF directly support the EOS Project, anyone interested in using RCF sources or services is encouraged to contact our group. Provided the proposed work advances NASA's interests, we will be delighted to work with you.

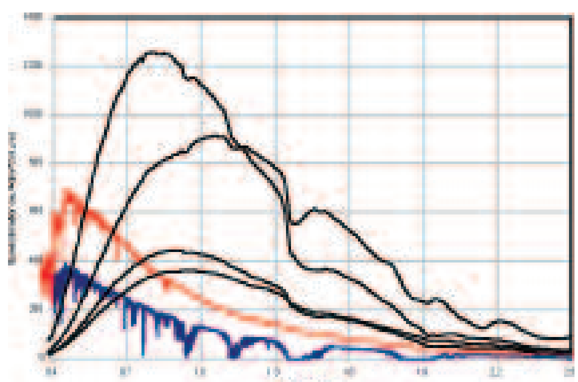

Figure 2. Maximum spectral radiance of main RCF sources (black). Extraterrestrial calculated spectra for an overhead sun are also shown, for White Sands, NM (blue) and for a perfect lambertian diffuser (red).

For more information, please see: Marketon et al, 2003.

Contact: Peter Abel, Peter.Abel@nasa.gov

Diffuser Calibration Facility Scatter Measurements in Support of Satellite Instrument and Field Validation Projects

NASA's center of expertise in the measurement of optical scattering is the Diffuser Calibration Facility (DCaF) located in Code 924. The DCaF is a class 10,000 cleanroom facility housing a unique suite of instrumentation capable of calibrating and characterizing optical scatter from a variety of materials. The facility features a unique, state-of-the-art scatterometer capable of measuring the bidirectional scatter distribution function (BSDF) and 8 degree directional/hemispherical reflectance from 230 nm to 900 nm of transmissive, reflective, specular, and diffuse optical elements and materials. The scatterometer is capable of also measuring granular, powdered, or liquid samples. The facility also houses an in-plane scatterometer capable of measuring the BSDF using lasers at 1150 nm and 1523 nm of vertically mounted samples, extending the facility measurement capability into the shortwave infrared. Lastly, the facility houses vacuum instrumentation capable of performing materials contamination/solar exposure studies on spaceflight materials. The DCaF is a secondary standards facility with BSDF measurements traceable to the Spectral Tri-function Automated Reflectance Radiometer (STARR) at the National Institute of Standards and Technology (NIST).

In 2003, NASA Goddard's DCaF provided optical scatter measurements to a number of Earth and Space science satellite and field validation programs.

In January 2003, the DCaF completed an extensive series of bidirectional reflectance distribution function (BRDF) and 8 degree directional/hemispherical reflectance measurements in support of field validation studies performed by the Commercial Remote Sensing Program (CRSP) at NASA's Stennis Space Center. Four CRSP tarp samples with reflectances ranging from 5 to 55% were measured at 4 wavelengths between 485 nm and 800 nm over a wide range of incident and scatter angles. The effect of orientation of the tarp weave relative to the direction and polarization of the incident light was also studied. These measurements have been successfully incorporated into the CRSP vicarious calibration models and have been used in their analysis of IKONOS and other commercial remote sensor data.Since 1993, the DCaF has been the primary facility for the measurement of ultraviolet (UV) optical scatter for NASA and NOAA ozone measuring satellite and validation instruments. This long-term affiliation with the ozone community continued in 2003 with the DCaF's measurement of reflective and transmissive, diffuse and specular optical elements in support of the Ozone Monitoring Instrument (OMI), the Ozone Mapping and Profiling Suite (OMPS), the Solar Backscatter UltraViolet/2 (SBUV/2) instrument, and Code 916 Radiometric Calibration and Development Facility (RCDF). In April 2003, the DCaF responded to a request from Koninklijk Nederlands Meteorologisch Institut (KNMI), the Netherlands, to measure their diffuser previously measured by the Nederlandse Organisatie voor Toegepast-natuurwetenschappelijk onderzeok Technisch Physische Dienst (TNO TPD) and used in the pre-launch calibration of OMI and OMPS. The DCaF measurements of this diffuser showed excellent agreement with the TNO TPD measurements and provided a second blind comparison of the BRDF measurements of the DCaF and TNO TPD. This study complemented an earlier comparison using the Total Ozone Mapping Spectrometer (TOMS) diffusers. The results of the BRDF measurements of this diffuser are shown in Figure 1.

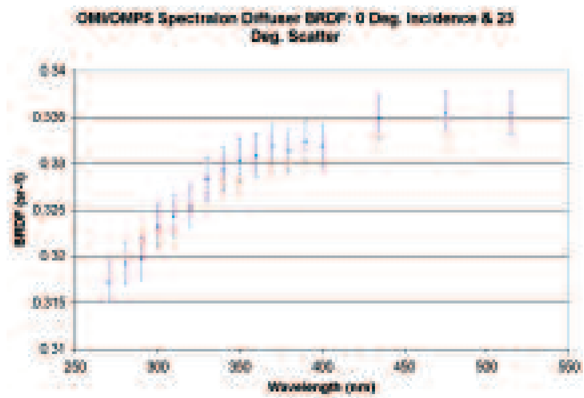

Figure 1. DCaF (blue triangles) and TNO TPD (red squares) BRDF measurements on a Spectralon diffuser used in the calibration of the OMI and OMPS satellite instruments. The BRDF measurements from the two facilities agree to within their combined measurement uncertainties.

In June 2003, the DCaF acquired BRDF data for the OMPS flight project on one reflective aluminum diffuser and bidirectional transmissive distribution function (BTDF) data on two limb diffusers constructed from microlens arrays and ground fused silica wafers. In support of the pre-launch cross-calibration of the OMI, OMPS, and TOMS instruments, the DCaF measured the UV BRDF of the three TOMS Spectralon diffusers in July 2003. In October 2003 at the request of the SBUV/2 project and Ball Aerospace, the DCaF measured the UV BRDF of two Spectralon diffusers and a powered collimating mirror.

The Stereo CORonograph-1 (COR-1) project in the Laboratory for Astronomy and Solar Physics has been a customer of the DCaF since 2000. In 2003, the DCaF played a key role in up-selecting and post-assembly testing of the COR-1 transmissive diffusers. In support of the COR-1 project, the DCaF measured the BTDF of 24 opal glass samples, 3 polarizer samples, and 8 fully assembled COR-1 diffusers.

Contact: Jim Butler, James.J.Butler@nasa.gov

Radiometric Validation and Round-Robin Campaigns in EOS Calibration

Since 1995, the Laboratory for Terrestrial Physics has provided technical support to the EOS Project Science Office in the calibration of satellite, airborne, and ground-based instruments. Key to this activity is the EOS Measurement Assurance Program (MAP) administered by NASA's GSFC and the National Institute of Standards and Technology (NIST). The EOS MAP includes radiometric measurement comparisons and artifact round-robins designed to critically evaluate the accuracy of EOS satellite and field instrument calibration and characterization.

For EOS satellite and field validation instruments operating from 400 nm to 2500 nm, the most common sources used in pre-flight radiance calibration are integrating spheres and diffuse reflectance panels illuminated by irradiance standard lamps. Since 1995, the MAP within the EOS calibration program has enlisted the expertise of NIST, the University of Arizona Optical Sciences Center's Remote Sensing Group (UA), Japan's National Institute of Advanced Industrial Science and Technology (AIST), and NASA's GSFC in an effort to validate the radiance scales of EOS instruments. Radiance scale validation is accomplished using stable transfer radiometers carefully characterized by each institution using a variety of techniques. In April 2003, the analysis of data obtained from 10 deployments of these transfer radiometers to international EOS calibration facilities was completed. The agreement between the radiance measurements made by these radiometers was ±1.80 % at 411 nm, ±1.31 % at 552.5 nm, ±1.32 % at 868.0 nm, ±2.54 % at 1622 nm, and ±2.81 % at 2200 nm. These levels of agreement are sufficient to validate the radiance scales of EOS sources with typical reflectance specifications of ±3.0 % (k=1).

In May 2003, analysis of data obtained from a deployment of NIST, UA, and NASA's GSFC transfer radiometers to Raytheon Santa Barbara Remote Sensing (SBRS) was also completed. This radiometric validation campaign, held in May 1998, was conducted in support of the calibration of the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) instrument. The SBRS radiance source used in the campaign will also be used in the calibration of the National Polar Orbiting Environmental Satellite System (NPOESS) and NPOESS Preparatory Project (NPP) Visible/Infrared Imager/Radiometer Suite (VIIRS). The radiometric validation campaign validated the SBRS goal of calibrating their radiance source to ±3.0 % in the visible and near infrared spectral regions. The SBRS scale was validated to ±4.0 % in those shortwave wavelength infrared regions not affected by water vapor absorption.

In July and September 2003, radiometers and sources from NIST and the UA were deployed to the United States Geological Survey (USGS) in Flagstaff, AZ, to validate the radiance scale assigned to the Robotic Lunar Observatory (ROLO) project. Since 1993, the ROLO visible/near infared and shortwave infared telescopes have acquired in excess of 85,000 lunar images in 32 bands for purposes of establishing the Moon as an on-orbit satellite calibration/cross-calibration source. The ROLO telescopes are shown in Figure 1. The ROLO radiance scale is currently based on an astronomical scale for the star Vega. Ground-based calibration of the ROLO telescopes was accomplished using a 16 inch diameter collimated radiance source. Using a hyperspectral transfer radiometer, the radiance of the collimated source was established relative to the radiance of an integrating sphere calibrated at the NIST Facility for Automated Spectral Radiance Calibrations (FASCAL). The collimator-based calibration of ROLO was then compared to the star-based calibration. In addition, the NIST transportable, tunable laser source called the Traveling Spectral Irradiance and Radiance Calibrations with Uniform Sources (SIRCUS) was used to validate the system level relative spectral responsivities of several ROLO channels. These data are currently being analyzed.

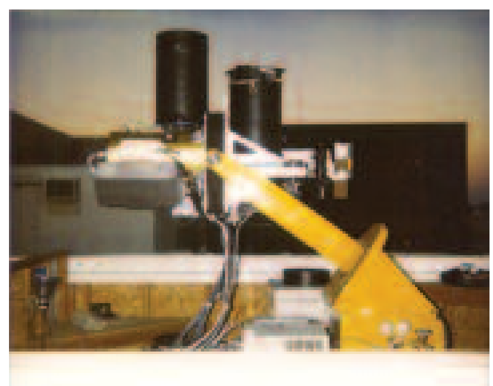

Figure 1. The ROLO visible/near infared (left) and shortwave infrared (right) telescopes viewing the zenith sky at USGS in Flagstaff, AZ.

In 2003, an EOS aperture area round-robin with NIST as the hub institution was conducted in support of the total solar irradiance measurement community. Preliminary results on apertures submitted by two institutions revealed biases of +0.013 % and +0.065% relative to NIST. This equates to a difference in total solar irradiance of 0.18 W/m^2 to 0.89 W/m^2 for a reference value of 1366.3 W/m^2.

Contact: Jim Butler, James.J.Butler@nasa.gov

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